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RESEARCH AND DEVELOPMENT OF AN ADVANCED PERSONAL LOAD CARRIAGE SYSTEM PHASES II AND III

Section E: Parametric Analysis of Advanced Personal Load Carriage Systems

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Parametric Analysis of Advanced Personal Load Carriage Systems

Executive Summary

Parametric analysis of load carriage systems has allowed for increased understanding of relationships between system design characteristics and the impact of these design features on the bearer. Of significant research interest for the APLCS project are the issues of convenience, comfort, and capacity Parametric design analysis in this phase of the project involved an evaluation of the effects of differing load placement on the centre of gravity and accessibility of kit, and the development of a computer model for optimizing load configuration, based on system centre of gravity

Kit placement, for both civilian and military load carriage, has only been subject to general guidelines in the past. This study looked at the bulkiness and accessibility requirements of certain kit items, along with the versatility of current LCS at containing these items, with the aim of improving future LCS design and function User group surveys and records of standard operating procedures provided models for kit placement, which were evaluated for location of centre of gravity and access to critical equipment Soldier kit preferences and frequency of use were also established.

Optimization of load distribution for carriage is subject to multiple criteria, including physical constraints, desired load location and resultant forces, and accessibility requirements Optimization software developed in this phase of the contract would allow for evaluation of varying LCS dimensions and kit combinations on target variables, such as contact forces It is also possible to evaluate LCS design features, for improved loading capability.

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1.0 Introduction

The Defence and Civil Institute of Environmental Medicine has contracted Queen's University to assist in the research and development of an Advanced Personal Load Carriage System (APLCS) as part of a Canadian Forces Soldier Modernization Program, a major crown project D6378 Integrative Protective Clothing and Equipment. The research team, collectively known as the Ergonomics Research Group (ERG), comprises members from the School of Physical and Health Education, and Mechanical Engineering at Queen's University, and associates in Industrial Engineering at DalTech, Dalhousie University, Halifax

It is recognized that soldier survival, sustainability, and performance in the field will often require carrying significant loads consisting of protective equipment, armaments and provisions for any future conflict or peacekeeping operations It is also recognized that soldier survival may depend on carrying heavy loads over greater distances, or moderate loads over shorter distances but where soldier performance is essential. Therefore, the next generation of PLCS should be designed to be compatible with the range of soldier physical, physiological and biomechanical capabilities for survival, as well as optimize soldier performance and operational effectiveness. To protect soldiers in this manner, it is necessary to develop a soldier system which can protect the soldier and equipment in these conditions.

Despite several decades of research into load carriage (Pelot et al., 1995, Knapik et al, 1996), very little of it is prescriptive for design improvements Most of it revolves around varying loads, march distances and/or terrain. These investigations certainly help to define human load carriage limitations, but the variables studied are generally quite insensitive to design changes There are many dimensions to consider when developing new LC designs (Figure 1.1 and Table 1 1), and the issues of convenience, comfort and capacity are the immediate concerns of the APLCS project Several studies have been conducted by ERG and others in recent years to understand the specific relationships between many design characteristics and their impacts on the bearer As described in other APLCS reports, measures such as strap forces and pressures, torsional stiffness, and trunk lean are affected by pack characteristics such as centre of gravity (CofG) of the load, suspension system

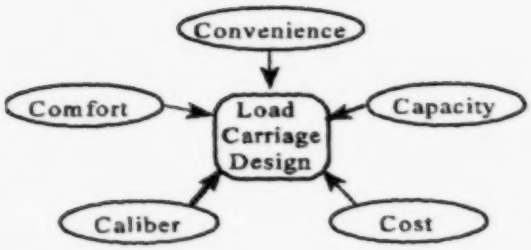

Figure 1.1. Dimensions of good personal load carriage design.

Table 1.1. Key load carriage design dimensions.

Dimension	Manifestation	Investigations
Comfort	forces on the body, local skin pressures, chafing, thermal effects	force and pressure measurements; temperature measurements biomechanical models, subject appraisals
Convenience	ease of access, versatility, modularity	accessibility of kit, attachment points, adaptability to various missions
Capacity	size, shape, compartmentalization	pack comparisons; subjective opinion; computer models, attachment points
Caliber	quality with respect to: durability, noise, camouflage, weather resistance, etc	STANAG, QSTAG, etc specifications, field tests, materials testing
Cost	R&D cost, initial cost of production; replacement parts	life cycle cost analysis; future adaptability

design, strap shape, and other variables Field trials serve to correlate laboratory measures with subjective opinions of comfort and performance, and give overall evaluations of a load carriage system All of these results are largely *descriptive*, in that they help us understand what the important pack factors are, and how they affect load carriage The next logical step is to incorporate this knowledge into *prescriptive* holistic models, which combine and apply the newly established relationships to create new designs.

The overall objective of this aspect of the APLCS project is to develop a framework and computer tools for evaluating the effects of parametric changes on load carriage design The basic elements of the model comprise a biomechanical model of load carriage, currently under development by ERG, a loading model to configure the load optimally for a given kit list, and a visualization component to examine and illustrate the results A single outcome (i e design) may be obtained for a given set of input criteria, or alternatively parametric analysis may be used to map the changes in several output measures over the full range of each input variable of interest. For example, given a constant pack volume, the impact of changing the width of the compartment (and hence the packing arrangement and CoG) on the shoulder strap forces can be estimated. These results complement laboratory and field studies in understanding the fundamentals of load carriage, and provide feedback for better load carriage designs.

The specific aims of this phase of the project were to evaluate the effects of load placement on the centre of gravity and accessibility of kit, and then develop a computer model which would optimize load configuration to achieve the most desirable CoG Eventually, this will translate into the most desirable force distribution on the soldier, once the optimization model is combined with the biomechanical model

2.0 Location of Kit Items

The purpose of the kit location study was to ascertain whether kit location had a significant impact on Centre of Gravity and/or accessibility If not, then one might assume that load carriage design may proceed without much reference to kit location, only total weight and volume Conversely, if kit location does affect CofG, then models to evaluate load carriage characteristics should allow for a realistic range of CofG. Furthermore, restrictions may be placed on kit location due to accessibility contraints reflective of operational readiness.

Amongst the many design criteria, the load carriage system should be designed to permit the most effective placement of kit items In the context of the Figure 1.1, kit location may be a major determinant of convenience, either due to frequency of use such as the canteen, or criticality such as the NBC gear. The load carriage capacity and kit location are also intrinsically linked, as the size and location of compartments, pockets and attachment points restrict the placement of objects Comfort may also be affected by kit location, sometimes directly such as when a piece of kit hampers movements or pokes the bearer, or requires awkward contortions to access, or indirectly as the forces and pressures on the soldier may be sensitive to kit location. Note that from the systems design perspective, the redesign of certain kit items could also improve their portability and this should be an important consideration as gear is being modified or introduced.

This study has been conducted to better understand and measure the attributes of desirable kit placement to improve pack design, allow flexibility for future needs, and to incorporate into a computer model of load carriage

2.1 Evaluation Framework for Kit Placement

General frameworks have been developed to encompass the most important elements of load carriage design. The ABCD system (Access, Balance, Compactness, Danger) applied to civilian pack evaluation reflects most of the considerations for kit placement In this case, danger refers to the placement of hazardous goods such as the excessive top-loading of a camp fuel container The military's Statement Of Requirements (SOR) stipulates additional and more rigorous standards than civilian packs. However, the standards for optimal kit location have not been thoroughly specified A number of criteria should be considered when evaluating kit placement

- *bulkiness:* measures include: volume, mass, dimensions, compressibility, deformability
- *accessibility:* decomposes into sub-criteria: frequency of use, criticality, ease of replacement
- *sturdiness*: may affect location
- *versatility:* dropping or adding kit items, adding or removing load carriage components
- *interference:* adversely restricting the soldier's functions, mobility and/or safety
- *doctrine:* any other military practices not governed by the above criteria

The purpose of this analysis is not to prescribe new procedures for current kit placement, but to thoroughly review loading requirements and strategies with the aim of improving future PLCS design and function These studies focus on the issues of load balance (centre of gravity) and accessibility of kit.

2.2 Effect of Kit Placement on Centre of Gravity

Studies have shown that the height of the centre of gravity of the load can have physiological consequences for the bearer, and that the best location depends on terrain, duration of march and other factors (see Pelot et al (1995) for literature review) Recent work by ERG has added to these results (Johnson, 1997) Determinants of centre of gravity include pack design, suspension system design and kit location. The current study focuses on whether centre of gravity is sensitive to kit location. Two experiments were conducted In the first, several packs containing essentially the same kit items were compared to examine the "natural" variation in centre of gravity as each soldier packed his load. In the second evaluation, the displacement of the centre of gravity using deliberate extremes in kit mass and location was examined.

2 2.1 Natural variation in backpack CofG

An inventory of kit items was collated by staff at DCIEM and some typical groupings were defined by season and trade Masses and approximate dimensions were assigned to each item The 2RCR (2nd Royal Canadian Regiment) Orders of Dress Operating Procedures were also reviewed for current practices. To determine whether various loading configurations have a significant effect on the centre of gravity, the following experiment was conducted The center of gravity in three dimensions (Figure 2 2-1) was determined for eight rucksacks packed by their respective owners with a basic summer kit list excluding rations and ammunition Each kit item was packed in the location specified in the 2RCR Standard Order of Dress Handbook for summer conditions with a few minor variations between rucksacks. The center of gravity was determined using a force board and portable scale (Figure 2 2-2)

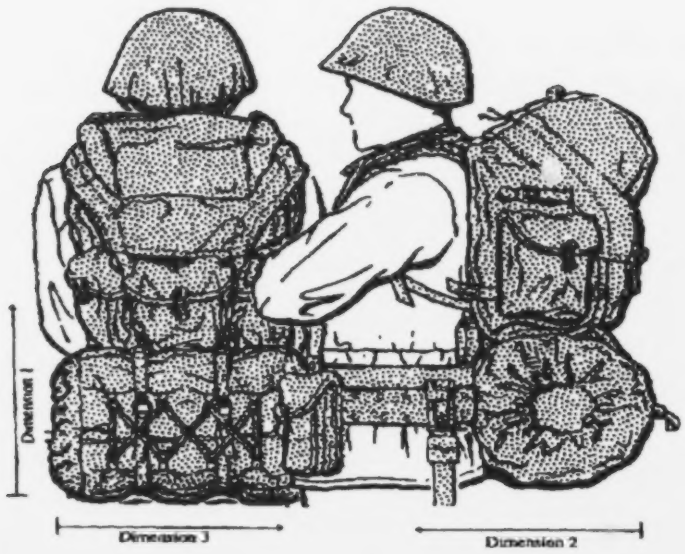

Figure 2.2-1. Co-ordinates for C of G reference

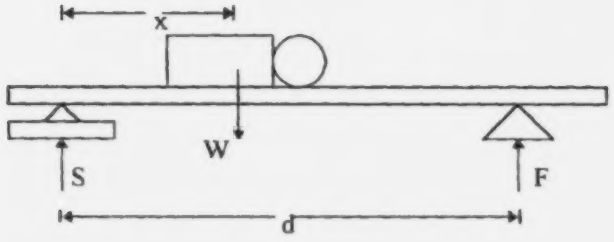

Figure 2.2-2. Scale for measuring C of G

The weight of the reaction board was compensated for in the determination by zeroing the scale after the force board had been set up. Each pack was laid on the force board while the weight was read from the scale The distance from the reaction force read from the scale (S) and the center of gravity of the pack was determined using the following equations

$$+\uparrow \sum F_y = 0 = S - W + F$$

$$+\circlearrowleft \sum M_s = 0 = Wx - Fd$$

where

S = point reaction force read from scale

x = distance to center of gravity from force S

W = weight of pack, determined by a hanging scale

d = distance between point reaction forces

F = point reaction force

The three dimensional center of gravity for each pack is summarized in Table 2 2.

Table 2.2. Mass and C of G for eight packs

Soldier #	Pack Weight (kg)	Scale Reading (kg)			Center of Gravity		
		Dimension			Dimension		
		1	2	3	1	2	3
1	18.2	7.7	11.8	8.6	49.5	30.1	45.2
2	17.5	6 4	9.5	7.3	54 7	39 1	50.3
3	17 7	8 6	11 4	8 6	44.1	30 9	44.1
4	19.5	7.7	11.8	9 1	52.0	34 0	46 0
5	19.1	8 0	10 9	6 8	50 2	36 9	55.3
6	17 3	8 6	10.5	6 8	43 0	33 9	52.1
7	21 4	6.8	11.4	7 3	58.6	40 3	56 7
8	18.6	8 2	11 4	7 7	48 2	33.6	50 3
MEAN	18.7	7 8	11 1	7 8	50 0	34 9	50 0
S D.	1.3	0 8	0.8	0 9	5 2	3 7	4 7

The average distance of the center of gravity from the bottom of the rucksack (Dimension 1) is 50 cm with a standard deviation of 5 2 cm This area is located just above the valise This may be due to that fact that the valise is packed fairly tightly compared to the rest of the rucksack when no ammunition and rations are packed. The average distance of the center of gravity from the front of the pack (Dimension 2) is 35 cm with a standard deviation of 3.6 cm This is close to the soldier's back and will be influenced partly by the metal frame. The mean distance of the CoG from side to side is 50cm with a standard deviation of 4 7cm from the opening of the valise.

Some of this variation is no doubt due to the relatively rough measuring system However, given that the measures were fairly repeatable, it shows that the centre of gravity is somewhat sensitive to kit location, even for a standard set of kit items To eliminate the variability of various soldiers' methods of packing, and the inaccuracy of measuring kit location directly, a computer simulation was run to examine the kit location issue.

2 2 2 Sensitivity of C of G to extreme kit location variations

The Canadian rucksack was loaded with typical summer kit, and the centre of gravity measured with the simply supported platform and a scale The load was then deliberately rearranged to alter the balance. The results were that the centre of gravity shifted noticeably, particularly in the vertical plane, despite the fact that the densest items, munitions, were not available to include in the test

Having established the potential relationship of the centre of gravity to kit placement, an approximate simulation model of the rucksack and kit was developed in AutoCAD to facilitate sensitivity analysis, repeatability, and reporting of kit location changes Each kit item was represented by a box with the same mass and approximately correct volume Eight different loading configurations ranging from approximately 11 to 27 kg. were evaluated The results are shown in Figure 2 2-3 (Hall & Pelot, 1996) *Normal #1* and *Normal #2* represent standard summer kit packed in two typical arrangements. *Extra heavy* puts additional weight distributed throughout the main compartment *Top heavy* concentrates extra weight in the top pocket and near the top of the main compartment *Bottom heavy* adds weight to the valise *Empty* represents the pack alone

Distributing the weight to the sides or to one side has little effect on the CoG in any direction This could change with the addition of ammunition, which is very dense.

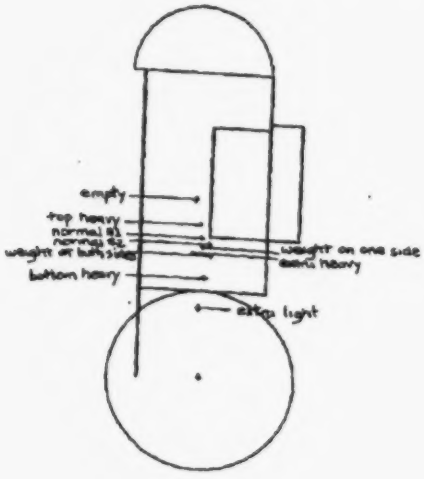

Figure 2.2-3. C of G for various loading configurations

The result is that the Centre of Gravity shifts only slightly along dimension 2 (front to back) and 3 (side to side) despite the major reconfiguration of the load, but in dimension 1 (vertical) the range was over 14 cm. This sensitivity to load placement would likely be exacerbated by heavy munitions load

These preliminary studies demonstrate that kit location may significantly alter the balance of the pack, and is therefore an important consideration for load carriage modelling. The ultimate effect of kit placement on soldier comfort is not yet known, and is the subject of ongoing studies In the United States, experiments are being conducted whereby a load affixed to a dummy by a load carriage suspension system can be shifted in the vertical or sagittal plane and the resulting load carriage forces measured (presented at Advances in Military Load Carriage Workshop, Queen's University, October 1996) The final results of this work have not been reported Meanwhile, the Ergonomics Research Group at Queen's is advancing its biomechanical model, which will ultimately convert load location and distribution into corresponding strap forces

2.3 Effect of Kit Placement on Accessibility

Although a soldier's comfort and performance may be enhanced by optimizing the centre of gravity of the load, the accessibility of certain kit items and the versatility of the PLCS in adapting to changes in the prescribed loading are very important as well

Some items need to be accessible during travel times, and others such as sleeping gear are only unpacked at destination To evaluate the accessibility, two measures are introduced criticality and frequency of use. The criticality is a major determinant in the placement of kit, as NBC gear and weapons take priority. Frequently used items, such as the canteen, should also be easily accessible

To evaluate these criteria in the field, a questionnaire developed at DalTech with the assistance of Major Linda Bossi, DCIEM, was administered to twenty soldiers at CFB Gagetown The survey listed kit which would be appropriate for a typical 3-day manoeuvre in the fall (Table 2 3) For each kit item, the soldiers were asked to indicate the maximum, minimum and typical number which would be taken on such an exercise Referring to diagrams of the rucksack and webbing, the soldiers indicated where each article was carried, and the advantages and drawbacks of the location Specifically, they were asked about the criticality and frequency of use The resulting locations are indicated in Table 2.3 and Figures 2 3-1 and 2 3-2 (see Day & Pelot (1996) for complete results)

When adhering to Standard Operating Procedures (SOPs), the soldiers were largely consistent in their placement of kit with certain exceptions When allowed to self-determine personal kit items, a wide range of preferences was noted. Some soldiers were willing to bear the increased load to allow additional clothes for warmth or a dry change, while other jettisoned practically all non-essentials There were a couple of kit items that the soldiers almost unanimously agreed were not useful and/or were in the way

One common practice is to place the shaving kit and other personal items in the valise (sleeping bag container) which is strapped to the bottom of the rucksack It is apparently much easier to simply toss the valise in the tent giving immediate access to sleeping bag and the other items stored within However, the valise was not designed for this, and the implications are that the centre of gravity is shifted to a lower and less desirable position, the valise tends to slip out of its restraining straps, and the balance of the entire load may be less stable

Table 2.3. Survey of Kit Location Pros and Cons.

	Kit Items	Total Carried					Accessibility
		Max	Min	Typical	Location as per SOP	Actual Location	1- Not Important 2-Somewhat Important 3-Important 4-Very Important
1	undershirt	3	1	2		9,10	1
2	1 pr. extra socks	1	1	1	14,15	14	3
3	other socks	6	4	4	9,10	1,9	2
4	Goretex socks	1	1	1	14,15	14,15,28	3
5	drawers	3	2	3	9,10,28	9	1
6	handkerchief	1	0	0	26	23,26	1
7	combat shirt	2	1	2	9,10	10,28	1
8	combat pants	2	1	2	9,10	10,28	1
9	belt	1	1	1		28	
10	suspenders	0	0	0			
11	combat sweater	1	0	0	9,10	9,28	1
12	other sweater	1	0	1		9,28	3
13	combat jacket, liner	1	0	0	9,10	9,28	3
14	combat jacket, outer	1	1	1	9,10	9,28	3
15	other liner	1	1	1		9,28	3
16	gloves,inner	1	0	0	14,15	14,26	3
17	gloves, outer	1	1	1	14,15	14,26	3
18	combat boots	1	1	1		28	
19	combat hat	1	1	1	26	26,28	3
20	green toque	1	0	1		9	1
21	beret	0	0	0			
22	combat scarf	1	0	0 5	9,10	1,2,28	1
23	Goretex inner gloves	1	1	1		14,26	3
24	contact gloves	1	1	1		14,26	3
25	jacket, wet weather	1	1	1	14,15	14	3
26	trousers, wet weather	1	1	1	14,15	14	3
27	laundry bag	0	0	0			1
28	outer poncho	1	0	1		14	3
29	C5 knife	1	1	1	29	26,29	3

Table 2.3. Survey of Kit Location Pros and Cons (cont'd...).

	Kit Items	Total Carried			Location as per SOP	Actual Location	Accessibility
		Max	Min	Typical			1- Not Important 2-Somewhat Important 3-Important 4-Very Important
30	pocket knife	0	0	0			
31	hunting knife	0	0	0			
32	compass	1	0	0	25	9,14	4
33	binoculars	1	0	0	slung	9,14	4
34	flashlight	1	0	0	9,10	1,2,25,30	4
35	commercial knife	1	1	1		26, pants belt	3
36	mosquito head net	1	0	1	11,12,13	11,12,13	1
37	mosquito repellent	1	0	1	14,15	14,26	2
38	mosquito bar	1	0	0	11,12,13	11,12,13	1
39	entrenching tool	0	0	0	outside 3,4		1
40	rope(50 ft)	0	0	0	9,10		
41	550 cord	1	1	1		Varies	2
42	foot powder	1	0	1	14,15	14	2
43	sunscreen	1	1	1		14,26	3
44	rations(1 meal)	3(stripped)			4-8,14,15	3-8,14	3
45	snacks					3-8,14	4
46	milmac cup	1	0	0	9,10	9,10	2
47	milmac plate	1	0	0	9,10	9,10	2
48	KFS	1	1	1	29	29	2
49	cup canteen w/ metal stove	1	1	1		19	2
50	canteen(1L)	1	1	1	19	19	4
51	canteen(4quart)	1	1	1		9,10	3
52	boot polishing kit	0	0	0	9,10		
53	sewing kit	1	1	1	9,10	9,10	1
54	field message pad	2	1	1		24,25	3
55	marker/pen/pencil	2	1	1		24,25	3
56	shaving kit	1	1	1	11,12,13	1,13	2
57	hand towel	1	1	1	11,12,13	1,13	2
58	bath towel	0	0	0			

Table 2.3. Survey of Kit Location Pros and Cons (cont'd...).

	Kit Items	Total Carried			Location as per SOP	Actual Location	Accessibility
		Max	Min	Typical			1- Not Important 2-Somewhat Important 3-Important 4-Very Important
59	wash basin	0	0	0			
60	field dressings	3	2	2	26	24,26	4
61	poncho liner(ranger blanket)	2	0	1	11,12,13	11,12,13	2
62	bivi bag	1	1	1	11,12,13	12	2
63	air mattress	1	1	1	11,12,13	Outside valise	2
64	utility sheet	1	1	1	11,12,13	13	2
65	valise	1	1	1	11,12,13	11,12,13	
66	sleeping bag, liner	1	0	1		11,12,13	2
67	sleeping bag, inner	1	0	1	11,12,13	11,12,13	2
68	body armor, frag vest	1	0	0		28	
69	wrist watch	1	1	1		28	4
70	matches/lighter	5	2	3		26	3
71	fuel tablets, package of six	1	1	1		14	2
72	cam stick	1	1	1	14,15	14,24,26	2
73	range card	2	2	2		23	2
74	ballistic goggles	Only in operations.				Clipped to flack vest.	4
75	coveralls,chemical warfare	1	1	1	27	27	3
76	boots, protective	1	1	1	27	27	3
77	gloves, protective, NBCW	1	1	1	27	27	3
78	decontamination mitts			2	27	27	3
79	chemical agent			2	27	27	3
80	vapor detector			0			
81	atropine injectors			0			
82	decontamination lotion			2		27	3
83	sachets NBCW			2		27	3
84	DT-60 personal dosimeter			1	27	27	3
85	gas mask w/canister	1	1	1	23	23	4

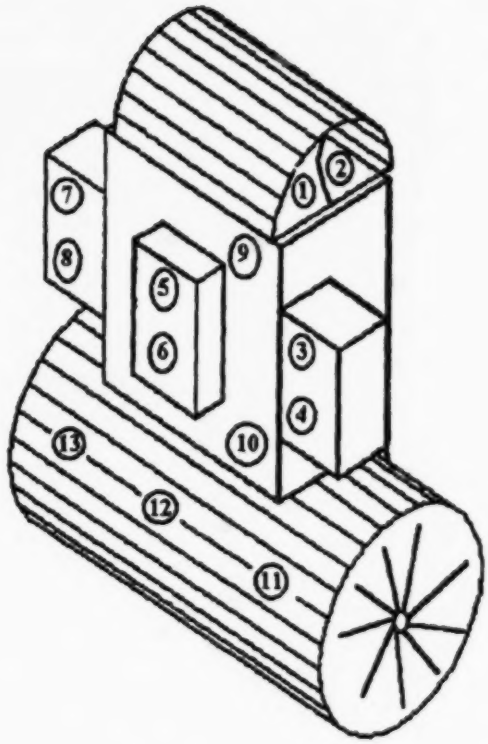

Figure 2.3-1. '82 Pattern Rucksack Numbered Sections

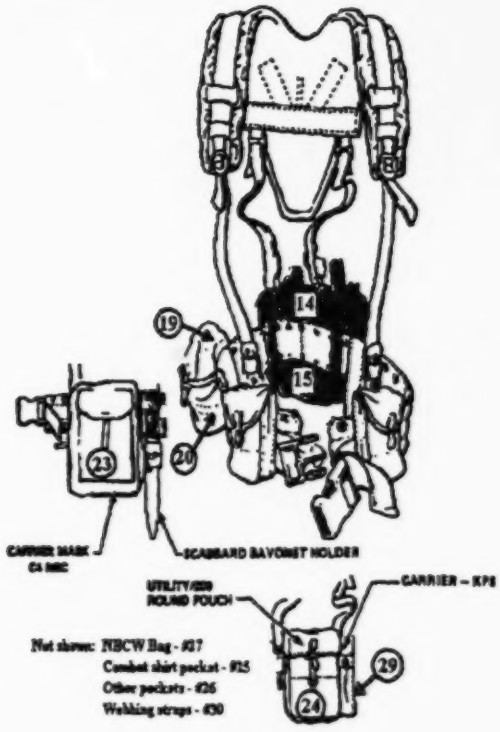

Figure 2.3-2. '82 Pattern Webbing Numbered Sections

Many items were categorized as critical, which severely restricts their placement, whereas other items, such as extra socks, can be stuffed just about anywhere The soldiers provided ratings on the relative frequency of requiring each article Canteen, rations, binoculars and rain gear are examples of frequently accessed items.

2.4 Discussion

A thorough understanding of kit placement practices is essential for effective PLCS and kit design The objective of this study was to determine the main characteristics of kit placement, and to develop a methodology for evaluating all of the pertinent criteria

The specific results of these studies are only preliminary Evidently, the centre of gravity is sensitive to kit placement, particularly in the vertical plane, but the translation of this into forces on the soldier has yet to be completed. Furthermore, moments of inertia have been calculated for the various configurations, but the effects on balance have yet to be ascertained

The criticality of a kit item should be paramount in placing the article, but frequency of use should also be taken into account to facilitate the soldier's task. The load carriage system should be designed to accommodate the widest range of kit possible, based on actual practice as well as prescribed procedures. Versatility in the LCS, with easily altered configurations, would allow the soldier to respond to a range of missions and environments. However, the design should optimize the basic kit loading as reflected by the above criteria

3.0 Development of Pack Optimization Software

3.1 Introduction

A computer model of a backpack system can serve as a very useful tool for design development Referring to Figure 1, simulations could be conducted to analyze various design attributes:

- *capacity:* given rucksack dimensions and compartments, how many kit items of various types may be packed? What different arrangements of kit are possible? Can new kit be accommodated?
- *convenience:* how can kit be arranged to permit best accessibility? Are pack dimensions cumbersome (too wide, too tall)?
- *comfort.* what are the predicted pressures on the bearer transmitted through the suspension system? Are the loads within acceptable limits? How does the load change with pack dimensions? How does the load change with kit location?

The development of such a computer model is at its initial stages Four principle components are required for a complete model: a kit placement optimization routine, a biomechanical model translating the masses and moments into forces on the bearer, criteria for acceptable or desirable limits on forces being transmitted to the soldier, and a graphics package to illustrate the results. A partial biomechanical model has been developed by the ERG, and work is ongoing in this area. Crude computer representations of a pack and common kit items have been developed in AutoCAD as described in the previous section. This section describes an initial computer formulation to automatically place prescribed kit items in a given rucksack based on criteria of accessibility and load balance

3.2 Optimization Criteria

The objective of this computer program is to provide a modelling and computational tool to evaluate the effect of three-dimensional loading configurations (in particular, backpack loading) considering multiple criteria These criteria include the following:

i basic physical constraints (fit, tightness, stability of packing);

ii balance, target centre of gravity (CoG) of load (aiming eventually at carrying comfort),

iii importance ranking (ease of accessibility, criticality) of packed items,

and possibly some other aspects

On the basis of such criteria, recommendations related to good ("optimal") packing strategies are to be made As a design aid, this computer simulation would permit the user to evaluate the effect of varying the pack dimensions as well as different kit combinations on the centre of gravity of the load carriage system, and ultimately the resulting forces on the bearer. For example, the static advantages of a tall narrow pack could be compared with squat versions for a wide range of kit Furthermore, the kit would not be considered simply as a point mass, but the moments of inertia, volumetric and accessibility constraints would be met.

3.3 Literature Review of Packing and Related Problems

The literature related to this study is drawn largely from the operations research journals. No articles have been found in the area of ergonomics nor any other discipline which might have an interest in load carriage This kit placement problem is closely related to packing and loading issues which are subjects of ongoing research in the operations research literature The usual context is to determine the best way to load a set of identical or non-uniform objects onto or into a carrier. Pallet loading and aircraft cargo loading are two common examples These problems are very difficult integer programming problems, and no general solution has been developed The usual approach is to develop a heuristic algorithm for a sub-class of problems whereby the objects are loaded sequentially making efficient use of remaining space This produces good, but not necessarily optimal, solutions

As it is well-known, stock cutting, material loading and packing problems in various contexts, are among the most important application areas of operations research For instance, the routine use of cargo containers and trucks represents a rather significant part (typically 5 to 15 percent) of the total operational costs in diverse industrial production or transportation environments.

Because of the general importance of this problem-class, and its prevalent modelling and numerical complexity, below we shall concisely review a body of professional literature related to this area. The discussion, hence, will not be restricted to the APLCS knapsack loading problem, with a view towards other potential application areas (such as, e g., pallet, truck, container, warehouse, railcar or air cargo loading and packing, just to name a few).

3 3 1 Some General Observations on the Problem Class

Although cutting (dissection), packing and loading 'puzzles' have been known for centuries, it is only recently that industrial and other cutting/packing/loading problems have been approached from a unified scientific point of view Perhaps the essays of Kantorovich (1939) and Brooks, Smith, Stone and Tutte (1940) are the first modern scientific works which deal with such problems, from an Operations Research (O.R.) perspective. Dantzig (1957) devotes a more generic discussion to optimization problems which, specifically, involve discrete - binary, or more general integer - variables, and indicates the inherent complications. Early work on industrial applications of cutting and packing strategies is documented, e g., by Paull (1956), Herrmann and Vajda (1957), Pierce (1964), and see also the important classical papers of Gilmore and Gomory (1961, 1965).

The great significance of this research area can be illustrated just by referring to some of its applications. Substantial reduction of wastage in textile, paper, metal, wood, plastic, glass, leather, etc industries, and/or new efficient packing, loading and transportation policies can be achieved, on the basis of a proper quantitative analysis of the underlying cutting/packing/loading problems

One can observe that, in generic modelling terms, all these problems can be described by a finite number of 'large' objects (stock sheets, containers, bins, trucks, or other resources), 'smaller' objects (items to be cut, packed, loaded, or tasks to be executed), and their efficient 'arrangements' (configurations, assignments) For this reason, they all belong to the broad area of combinatorial

optimization (CO). The essential numerical problem facing the researcher in CO is that the (in principle finite) number of possible configurations quite typically is prohibitively large this circumstance excludes the possibility of determining the 'best' arrangement by a direct enumeration technique To illustrate this point by a very simple example, one can think, for instance, of the possible sequential orderings of n objects (denoted by n factorial, or n!). Let us show below just a few values of n!, and observe the tremendous rate of increase in the possible arrangements

5!= 120

10!= 3,628,800

15!= 1,307,674,368,000

20!= 2,432,902,008,176,640,000.

The example shows that - except for very small and/or tightly structured CO problem instances - a simple listing and ranking of the alternative arrangements (feasible solutions) is not viable One can also reasonably expect that the same conjecture remains valid, even if the available computational power steadily increases

Cutting/packing/loading problems appear under various names in the Industrial Engineering (IE) and O R. literature. Aside from the ones already mentioned, further examples are. assortment, depletion, trim-loss, bin or strip packing, vector packing, rectangular packing, partitioning, job scheduling/timing and sequencing, resource allocation, part-nesting or layout design problems, etc Some of the most well-known CO problem-types - relevant in the present context - include the following.

- Knapsack problem (KP)

The objective in the KP is to cover ('pack') a long piece of material (the 'knapsack') by selecting objects of smaller length from a given set, in order to maximize the total 'value' of the covering pieces. The KP is often part of more realistic and more complicated packing/covering problems Note also that due to its one-dimensionality and very simple structure, it is easy to select nearly optimal solutions of the KP, applying some 'greedy' (myopic) heuristic 'Greedy' heuristic strategies play an important role in solving CO problems, and will be briefly discussed later The KP can be directly generalized to higher dimensional packing problems It is to be emphasized, however,

that in CO the transition from one dimension to 2D, 3D (or higher dimensions) is not a question of simple linear - or even polynomial - increase of complexity.

- One-dimensional loading (bin packing) problem

This is a straightforward generalization of the KP. several 'knapsacks' (bins) are to be 'packed', instead of one, with a similar objective to that of the KP. Obviously, the loading problem can also be generalized to higher dimensions.

- Cutting-stock problem

This problem involves cutting of a given order of required pieces from a set of stock sheets On the strategic level, the stock sheet sizes need to be selected (assortment problem) On the tactical level, appropriate cutting patterns are to be determined to meet a given order while minimizing wastage· this is the so-called trim-loss problem

There are many other important CO problems which, although similar in their essential structure and complexity to the abovementioned but outside of the scope of this study, will not be discussed here in any detail (consult for example, one of the standard O.R textbooks, such as Hillier and Lieberman (1986), or Winston (1994))

Given the sheer combinatorial challenge of ordering/sequencing a large number of objects, plus the very rapid (exponential) complexity increase, as a function of the physical problem dimension, it comes as no surprise that even the simplest, but somewhat realistic CO problem-instances are already NP-complete. In other words, they belong to a general class of combinatorial optimization problems for which it is widely accepted that they cannot be solved by any algorithm in a polynomially increasing effort (related to the size of the problem). For a detailed classical discussion of complexity issues in CO, see Garey and Johnson (1979) Of course, additional realistic conditions - other than simple rectangular objects, several conflicting objectives related to admissible configurations, etc - may significantly increase the problem complexity Therefore heuristic solution approaches have been suggested and developed along with 'exact' model formulations

Note that much of the early work in CO was devoted to worst case analysis (WCA) In these, the 'goodness ratio' of a heuristic solution to the theoretically optimal solution is considered, taking the worst possible problem instance (e g , Johnson, Demers, Ullman, Garey and Graham (1974), or the survey of Garey and Johnson (1981)) Although WCA is of considerable theoretical interest and it has certain practical implications, it is often more important to know how a given solution

procedure will perform on average With respect to the latter issue, consult the discussion of global optimization problems of closely related complexity by Wasilkowski (1992), or more specifically the paper of Coffman and Shor (1990) on the average-case performance analysis of 2D cutting and packing problems. Many of the average case studies, in which problem instances are generated according to a given probabilistic description, indicate that some suitable ('reasonable') heuristics, in fact, may work quite well Of course, the only way to determine good approaches to specific problems is to perform tests using 'typical' input data sets, since both the underlying CO problem structure and the imposed probabilistic assumptions can influence the results quite substantially

In general, as the complexity of the problem grows (in terms of dimensionality, number of objects to be arranged, and of possible additional considerations such as stability, accessibility, etc), the role of heuristic strategies and their average efficiency seem to increase Many practical approaches have been based on a series of ad hoc rules, often imbedded into a relatively simple, general mathematical model description of the underlying problem At the same time, it is also true that even simpler structured heuristic procedures will most often outperform manual 'trial and error' methods. Intelligent exhaustive or (semi)heuristic search methods of relevance can be based upon branch-and-bound strategies, simulated annealing, tabu search, neural networks and genetic algorithms, etc. (see for instance, Bellman (1982), Van Laarhoven and Aarts (1987), Glover (1994) or Pintér (1995a) on these approaches)

Following the above brief general introduction to and characterization of CO problems, the literature reviewed is summarized below The articles will be discussed in order of appearance in professional journals

3 3.2 Articles Reviewed

Christofides, Mingozzi and Toth (1978) discuss the general class of loading problems, in which abstract (non-specified) 'items' need to be packed into 'boxes' of different capacities In particular, they investigate the task of filling liquids into tanks of a given farm in a cost-efficient manner. Both static and dynamic versions of this problem are investigated, on a tactical (operational) level They formulate integer programming problems to describe these model variants The corresponding problem sizes can easily become quite large, but in many cases exploitation of the specific structure leads to effective problem size and/or complexity reduction The subject of this paper is not of immediate relevance to the present APLCS project. It provides however, insight into the combinatorial character and potential complexity of exact problem formulations and rigorous solution approaches (based on integer programming and graph theory).

Note that in great many cases, orthogonal cutting and packing patterns are considered only· that is, a number of rectangular objects need to be placed into a larger rectangle, with their sides parallel to the corresponding edge of the embedding rectangle This requirement, mutatis mutandis, essentially holds also in our present 3D packing problem. De Cani (1978) shows in a brief technical note that in certain cases improved cutting strategies can be given, when omitting the orthogonality criterion

George and Robinson (1980) suggest a heuristic algorithm for packing boxes into a container The boxes are ranked according to several adaptively selectable, and semi-heuristic criteria The basic underlying objective of their approach is to build vertical columns ('walls') of boxes, starting from the inner side of the container. This heuristic algorithm was tested (at the time of the study) on sets of up to 20 box types, modifications of the approach have been applied subsequently also by other researchers.

Magazine and Chern (1984) prove that the even the simplest instances of the multi-dimensional KP are NP-hard This result is of more theoretical character, without immediate relevance to the present study; however, it indicates again the expected complexity of 3D packing, as well as of many other CO, problems

An exact two-dimensional 'non-guillotine' cutting procedure is suggested by Beasley (1985) The terminology 'guillotine cut' means that cuts of the stock are executed parallel to one of the stock

edges, from one orthogonal edge to the opposite edge. In the 2D cutting problem studied by Beasley, a large rectangular stock piece is to be cut into a number of given smaller rectangles in such a way that the total size (or some other aggregate value) of the pieces cut out is maximal Obviously, the APLCS loading problem can be related to 3D, 'non-guillotine' cut based, orthogonal cutting procedures The basic integer programming model form presented bears direct relevance to our problem, and can be extended to three dimensions. However, the resulting problem size could be prohibitively large, unless the special problem structure can be exploited With this in mind, so-called normal patterns in which subsequent objects are moved as close to already located ones as possible, are considered. Model generalizations such as multiple stocks or stock defects, less relevant in the present context, are also discussed, together with a sophisticated (combined Lagrangean relaxation, subgradient and tree-search based) solution procedure. Illustrative computational results are presented for very small, randomly generated test problems (5 to 10 cutout items)

Israni and Sanders (1985) compare the performance of several relatively simple rectangular layout (cutting-stock, parts-nesting) heuristics, with a view to increase their applicability in manufacturing They are explicitly looking for strategies which are easy to understand and quick to apply They also investigate the effect of limited human interaction within given layout strategies On the basis of simulated numerical case studies in which the problem-instances are generated following a set of probabilistic conditions, it is concluded that human judgment can improve the solution quality (in terms of resulting trim-loss) quite substantially. This also has potential applicability to the APLCS kit loading problem as certain criteria such as accessibility and compressibility may not be rigorously quantified

Stacking and handling of identical size containers is studied by Sculli and Hui (1988) Their simulation analysis considers container storing and transportation moves in a harbour cargo storage environment, which apparently has only limited relevance to the present study A major conclusion of the paper, however, seems to have implications related to our project They suggest that the base storage area should be 'maximized', while its height should be as small as reasonable this structure is likely to reduce the unnecessary shuffling of the packed items Of course, in APLCS functional limitations will apply to the dimensions, but a suitable sensitivity study, including backpack size and possibly also other aspects, could be useful.

Han, Knott and Egbelu (1989) consider another heuristic approach to the 3D cargo-loading problem. Conceptually, they want to maximize the number of smaller identical rectangles (boxes) packed into a large rectangular prism (the loading volume) Loading is done by layers, more precisely, at each major iteration step by filling up an L-shaped (3D) volume which leaves a smaller 'brick' area to be packed at the next major step. Although the condition of identically sized items poses a serious restriction which is not likely to be of much relevance in our case, the heuristic packing strategy suggested may serve as a good starting point of other heuristic load sequencing methods

Bischoff and Marriott (1990) present a comparative evaluation of 14 heuristic rules applied in container loading: the objective is to minimize the total container volume (length) to accommodate a given cargo of 'boxes'. In an extensive numerical test, each heuristic procedure is applied to problems with 1-5, 10, 15 and 20 different types of boxes, taking an order of 500 boxes in all examples The comparison of the heuristic packings considered indicates very noticeable differences between them, clearly showing some superior (and inferior) choices. Suggestions for workable compound heuristics are also made

Coffman and Shor (1990) provide valuable insight into the average-case analysis of cutting and packing algorithms. Although their study is most closely related to problems in two dimensions, some of the heuristics discussed can be extended to the typically far more difficult 3D case. The described general methodology of probabilistic analysis is only of theoretical interest in the present context, since we deal with given kits of fixed size items In other related problems such as truck pallet loading, parcel delivery, etc., the relevance of the study is more obvious

Dyckhoff (1990) offers a systematic typology of cutting and packing problems, integrating various kinds of problems and notions in a unifying framework. The typology suggested allows the identification of common properties and main distinctive features of many specific problems The characteristics analysed include the following:

- physical problem dimensionality
- quantity measurements (discrete or continuous shape of objects considered, their regularity, form, size, orientation)
- assortment (permitted configurations)
- availability considerations
- pattern restrictions
- assignment constraints
- objectives
- reliability and variability of information (problem structure)

On the basis of the typology introduced, a symbolic description of several well-known problems is provided, with a view towards finding corresponding suitable solution approaches On the interconnection of CO problem-types and solution strategies, see also Gilmore (1979)

Gehring, Menschner and Meyer (1990) examine the problem of packing pooled shipment containers Similarly to George and Robinson (1980), they also utilize a 'wall-building' heuristics Boxes are first placed across the container width, and then upwards The volume and shape of the packing items is used to determine the ranking process, with added heuristic to account for improved weight distribution

Haessler and Talbot (1990) present a heuristic procedure for sizing customer orders and developing load diagrams for rail and truck shipments of consumer products (unspecified in the paper) These products are often characterized by low density, so that in most cases available volume limits the amount of products loaded into vehicles The procedure is based on careful vehicle and item dimensionality considerations, and a number of special problem decomposition and heuristic rules (since usual heuristics are deemed to be inferior) The computerized system includes the load assignment program, expressed by some 5000 FORTRAN code lines, plus a separately developed, but connected data management system This implementation allows to determine loadings which are confirmed, in real-time, by the ordering customer.

Chen, Sarin and Ram (1991) consider the pallet loading problem, for various box (load) sizes This task is interpreted as a 2D non-guillotine cutting-stock problem, since their model does not permit the loading of boxes on top of each other An exact optimization model is formulated minimize the number of pallets necessary to transport a given set of boxes which must not overlap when placed on the pallets This model, with appropriate 3D extensions, appears to bear direct relevance to the APLCS Project Note, however, that other physical constraint types will also be necessary in APLCS, aside from those considered in the paper.

Dowsland (1991) provides a discussion of 3D packing models, reviewing several solution approaches which are mainly based on heuristic elements. It is emphasized that results from 2D analyses may provide valuable information and basis for solving more complex 3D problems

In a theoretically oriented paper, Rhee and Talagrand (1991) investigate the multi-dimensional optimal bin-packing problem. Assuming random instances of rectangular items to pack, under proper independence assumptions they provide a theoretical characterization of the average number of bins needed to accomplish vector or rectangular packings of these items

The review by Dowsland and Dowsland (1992) considers a diversity of packing problems, varying from pallet loading and container stuffing to related placement tasks Exact and heuristic methods are concisely reviewed, focusing on 2D and 3D problems The survey covers nearly 150 works - books and research articles - related to the subject

Ngoi, Tay and Chua (1994) describe a new method of packing boxes into a container, with the objective of maximizing space utilization. Since theoretical 3D loading models tend to be complex and computationally intensive, they apply heuristics to sequence the items A new spatial representation technique, due to Ngoi and Whybrew (1993), is applied to describe the currently available packing space, at each stage This information is used to select the next packing object which 'best' matches one of the rectangular spaces left in the container, according to a set of rules Although this remarkable heuristic does not apply directly to our case (viz., its authors do not consider weight balance and centre of gravity location aspects) the approach most likely can be extended to include additional criteria. For instance, weight and centre of gravity both can be aspects when ranking the load items Of course the resulting heuristic will become more complicated and subjective, due to the needed additional external parameterization

Sweeney and Ridenour Paternoster (1994) provide a categorized research bibliography on cutting and packing problems. More than 400 professional books, articles and reports are included, with a view toward applications. Categories are defined by the dimensionality of the problems which can be studied within the framework of their approach, and by the solution methodology applied

Vasko, McNamara, Newhart and Wolf (1994) examine the optimal assignment of structural steel shapes (packed in drafts) to rail cars. Weight and dimensionality (load width/height) constraints are considered, together with constraints describing the required 'closeness' of unloading destinations Under these constraints, they maximize the utilization of the rail car park (as expressed by two jointly considered objective functions) The resulting large integer programming problems, having 5000 to 16000 binary variables, are then solved approximately by a heuristic algorithm An application of this methodology at the Bethlehem Steel Corporation (USA) is summarized, presenting illustrative numerical results related to specific loading/unloading problems.

To sum up the findings of this short (and certainly not exhaustive) review, one can clearly distinguish between the two main approaches followed: exact and heuristic Exact models, based on integer, mixed integer, or dynamic programming formulations are frequently introduced Their primary limitation lies in the unavoidable computational complexity issues which typically become apparent even for moderate problem sizes. For this reason, and sometimes also in lack of exact model formulation, heuristic solution approaches can play an important role The main difficulties in applying the latter arise from their very significant dependence on problem specifications and heuristic details, so that the quality of results may not be known. Moreover, they can not always be simply transformed to solving other even apparently similar problems. As there is no standard procedure nor any commercial software which can directly solve this class of problems, part of this study involves developing specialized solution techniques, though commercial software can be usefully applied to portions of the procedure

3.4 Optimization Model Formulation

3 4 1 General formulation overview

Using quantitative modelling terminology, the basic task can be expressed as follows given a physical load area (a three-dimensional volume of given shape) and a number of objects, place these objects into the load area in an 'optimized' fashion, as determined by a given set of criteria

- *Input data:*

  Container: 3 dimensions and mass

  Kit 3 dimensions, mass and accessibility rating (given say 3 classes of priority) for each item

  Target location centre of gravity. the user specifies the "ideal" CoG for combined container and kit. This can be derived from a biomechanical model of forces on the bearer, once completed, or a series of varied CoGs to study the sensitivity to kit location

  Target attractor point: to keep objects from "floating in the air" and/or having large gaps between them, a point is defined (typically in the bottom centre of the pack) to which the kit items are attracted.

- *Objective function:*

There are several objectives to be satisfied simultaneously

1 minimize the sum of the absolute values of the difference between each item's centre and the "attractor point" to keep objects from floating,

2 minimize the Euclidean distance between the aggregate centre of gravity of all of the kit items plus the container and the prescribed centre of gravity,

3. maximize the relative accessibility of higher priority items.

The "prescribed centre of gravity" is currently used as a surrogate measure for balancing the load in the best manner That is, since the relationship between centre of gravity and forces on the bearer has not yet been established through the biomechanical model, the analyst prescribes where the CoG is to be located, and the program attempts to achieve this. As this choice may be somewhat arbitrary, a sensitivity analysis may be conducted to examine the effect of varying the centre of gravity on optimal kit location.

Technically speaking, the program's goal is to determine the combination of decision variables (see below) which will best optimize the above criteria, subject to constraints on the system When there are several objectives, one may be retained as the optimization criterion and the others converted to constraints, or they may be combined into a single objective function with the user assigning a suitable magnitude to each element. The complete mathematical formulation is provided in Pintér & Pelot (1996)

- *Decision Variables:* These are the values that the computer must produce as output:

  Southwest vertex of each item

  Orientation of each item

  These outputs will completely specify the location of each kit item in the container

- *Constraints*:

  Basic physical bounds on location of items (i.e ensures that items are completely within pack boundaries);

  Non-overlapping packing of items to ensure that no parts of any two items occupy the same physical space This constraint is formulated by ensuring that in at least one of the orthogonal directions the distance between the centrepoints of two objects is greater than half the sum of their widths;

  Accessibility (priority ranking)· the current version requires that the top of any higher priority item not lie below the top of any lower priority item.

3 4.2 Model Components

In the following a new model is presented for three-dimensional packing The ergonomically essential requirement related to the resulting center of gravity location inevitably calls for an exhaustive search scope This, in turn, implies the need of an exact model formulation, and global search strategy Consequently, although strategies such as

- 'keep center of gravity as close as possible to desired location', when placing next object,
- 'fit and balance at each step',
- 'load objects in ascending order of importance',
- 'load objects, considering their aggregated merit'

can also be suggested, it is not clear whether their application would lead to near-optimal or even acceptably good packing strategies, in the present application area

For reasons of simplicity, we shall assume that a rigid, rectangular volume (box, prism) is to be packed by a given selection of smaller rigid, rectangular items. This way

- the packing of separate compartments (backpack pockets) is considered separately, by associating *a priori* a collection of packing items with each compartment;
- the main packing volume is approximated by a rigid prism - in reality, it has a trapezoidal shape, and it allows for a certain amount of elasticity,
- all packing items are considered to be rectangular - in reality, some of them are cylindrical, but they can always be embedded into a 'tightest' approximating box,
- each item is packed in an orthogonal orientation

Note that there is no theoretical obstacle to extending the model in order to handle also the aspects listed above, but the complexity would increase, possibly to a significant extent

The backback (or object 0), is characterized by its edge or border lengths B_1^0, B_2^0, and B_3^0 of fixed orientation, where the subscript denotes the axis; the corresponding size vector is denoted by $\mathbf{B^0}$. For unambiguity, we shall assume that the South-West (SW) corner of the pack, which corresponds to the closer bottom left corner of the backpack when facing the bearer, is located at $\mathbf{U}=(0,0,0)$; hence, the diagonally opposite North-East (NE) vertex is $\mathbf{V}=(B_1^0, B_2^0, B_3^0)$ The mass of the (unloaded) packing object is denoted by m_0

Similarly, the size of all objects O_i, i=1,...,I to be packed is described by their respective edges $\mathbf{b_i}=(b_{i1}, b_{i2}, b_{i3})$ Since we shall not assume a predefined orientation of O_i, for unambiguity one can assume that $b_{i1} \le b_{i2} \le b_{i3}$, resolving ties as needed. Note that the case of fixed orientation objects can also be handled in the framework presented in fact, orientation constraints directly lead to model simplifications and size reductions

We shall use index j=1,2,3 to denote the coordinate directions, moreover, we also introduce a standard fixed order of these directions Then, for instance, the orientation triplet {2,3,1} associated with object O_i denotes the fact that for the corresponding position of O_i , its edges are arranged along the coordinate axes in the order b_{i2}, b_{i3}, b_{i1} This way, assuming that the SW corner of O_i is $\mathbf{u_i} = (u_{i1}, u_{i2}, u_{i3})$, then its NW vertex is $\mathbf{v_i} = (u_{i1} + b_{i2}, u_{i2} + b_{i3}, u_{i3} + b_{i1})$ Obviously, there exist $3!=6$ possible orientations of each rectangular object considered index k will be used to denote these orientations

Now, the position of each packing item O_i is completely determined by its SW corner, $\mathbf{u}_i = (u_{i1}, u_{i2}, u_{i3})$, and its given orientation. We shall define the orientation indicator vector $\mathbf{d}_i=(d_{i1}, d_{i2}, d_{i3}, d_{i4}, d_{i5}, d_{i6})$, applying a lexicographical ordering of the orientation triplets That is, with respect to O_i

d_{i1} corresponds to triplet 1 ={1,2,3} d_{i2} corresponds to triplet 2 ={1,3,2}

d_{i3} corresponds to triplet 3 ={2,1,3} d_{i4} corresponds to triplet 4 ={2,3,1}

d_{i5} corresponds to triplet 5 ={3,1,2} d_{i6} corresponds to triplet 6 ={3,2,1}

We shall define $d_{ik}=1$ if the position of O_i corresponds to the orientation triplet k; and $d_{ik}=0$ otherwise

The mass of each packing item will be denoted by m_i Additionally, for each i, an accessibility index (importance rank) R_i is given Item O_{i1} is less important than O_{i2} ,denoted by $O_{i_1} \prec O_{i_2}$, if and only if $R_{i_1} < R_{i_2}$ Note that the relation $\prec$ defines only a partial ordering, since items in the same class are not compared

Finally, we are given a target location for $\mathbf{CM}^0$, the centre of mass of the total load Its calculation, of course, includes not only the packed items, but also the pack itself.

A packing pattern is called normal if the packed objects are moved as close to each other as possible For assuring unambiguity, one can require that they are tightly arranged with respect to a preassigned point $\mathbf{T}^0$ within the packing volume In different loading applications, this point may vary accordingly For instance, in a container loading context, the SW container corner U can be chosen as $\mathbf{T}^0$ (aiming at economical packing of the container volume) In the present project - aiming at balanced packing - a symmetrically located point $\mathbf{T}^0$ is more appropriate

Given the information listed above, we seek for such non-overlapping, orthogonal, non-guillotine cut and normal packing configurations which are physically stable, meet the given accessibility order criteria, and the resulting centre of gravity is as close to $\mathbf{CM}^0$ as possible We shall formulate below a corresponding mathematical model based on the notation introduced

Basic physical location constraints:

Location of SW vertex of objects:

$u_{ij} \geq 0$ for all i=1,...,I, and j=1,2,3.

(The number of these non-negativity constraints is 3I.)

Orientation of objects:

$d_{ik} = 0$ or 1 for all i=1,. ,I, and k=1,.. ,6,

$$\sum_{k} d_{ik} = 1 \qquad \text{for all } i=1,...,I.$$

(6I binary relations, and I constraints)

Next we shall describe the position of each item O_i, as determined by its SW corner position and orientation Let us introduce the notation L_{ij} for the actual edge length of O_i, given the vectors $\mathbf{u}_i$ and $\mathbf{d}_i$, and denote by $\mathbf{v}_i^{T}(v_{i1},v_{i2},v_{i3})$ its NE corner Then it is elementary to verify the following relations

$$\begin{aligned}
L_{i1} &= d_{i1}\cdot b_{i1} + d_{i2}\cdot b_{i1} + d_{i3}\cdot b_{i2} + d_{i4}\cdot b_{i2} + d_{i5}\cdot b_{i3} + d_{i6}\cdot b_{i3} \\
v_{i1} &= u_{i1} + L_{i1} \\
L_{i2} &= d_{i1}\cdot b_{i2} + d_{i2}\cdot b_{i3} + d_{i3}\cdot b_{i1} + d_{i4}\cdot b_{i3} + d_{i5}\cdot b_{i1} + d_{i6}\cdot b_{i2} \quad \forall\ i=1,...,I \\
v_{i2} &= u_{i2} + L_{i2} \\
L_{i3} &= d_{i1}\cdot b_{i3} + d_{i2}\cdot b_{i2} + d_{i3}\cdot b_{i3} + d_{i4}\cdot b_{i1} + d_{i5}\cdot b_{i2} + d_{i6}\cdot b_{i1} \\
v_{i3} &= u_{i3} + L_{i3}
\end{aligned}$$

(6I state equations)

The resulting NE vertex coordinates have to satisfy the inequalities.

$v_{ij} \leq B_j^0$ for all i=1, ..,I, and j=1,2,3

(The number of these constraints is again 3I)

Non-overlapping location of objects:

Given u_i and v_i, the centre $c_i = (c_{i1}, c_{i2}, c_{i3})$ of object i is given by.

$$c_{ij} = (u_{ij} + v_{ij})/2 = u_{ij} + L_{ij}/2.$$

(3I state equations)

Consider now an arbitrary pair of objects, O_{i1} and O_{i2}; for unambiguity, we shall assume that $i_1 < i_2$. Their non-overlapping configuration is guaranteed, whenever the object centres are 'sufficiently far' from each other. Since the packing is orthogonal, this condition is satisfied, if at least one of the following relations is valid:

$$|c_{i_1,1} - c_{i_2,1}| \geq \frac{L_{i_1,1} - L_{i_2,1}}{2}$$

$$|c_{i_1,2} - c_{i_2,2}| \geq \frac{L_{i_1,2} - L_{i_2,2}}{2}$$

$$|c_{i_1,3} - c_{i_2,3}| \geq \frac{L_{i_1,3} - L_{i_2,3}}{2}$$

In other words, the fulfillment of at least one of the above three inequalities is a necessary and sufficient condition for characterizing an orthogonal non-overlapping arrangement of O_{i1} and O_{i2}. The number of these constraints is 3I(I-1)/2, but there are ways to (formally) reduce this number. For instance, introducing the notation

$$g_{i_1,i_2,j} = |c_{i_1,j} - c_{i_2,j}| - \frac{L_{i_1,j} - L_{i_2,j}}{2}$$

(3I(I-1)/2 state equations),

equivalent constraints can be expressed by

$$\max_{j} \; g_{i_1,i_2,j} \geq 0 \qquad \text{for all } i_1,\ i_2 \text{ where } i_1 < i_2$$

(I(I-1)/2 constraints),

Observe, however, that although the problem size is formally reduced, the resulting new constraints are more complicated than the original ones

Since the constraints introduced above are nonlinear, as an alternative we shall also provide an integer, linear reformulation. Let us define first a decomposition to deal with the absolute value function

$$c_{i_1,j} - c_{i_2,j} = h^{+}_{i_1,i_2,j} - h^{-}_{i_1,i_2,j}$$
$$\text{where } h^{+}_{i_1,i_2,j} \geq 0 \qquad h^{-}_{i_1,i_2,j} \geq 0$$

Then the conditions $g_{i_1,i_2,j} \geq 0$ can be equivalently rewritten as

$$\frac{L_{i_1,j} + L_{i_2,j}}{2} - (h^{+}_{i_1,i_2,j} - h^{-}_{i_1,i_2,j}) \leq 0 \qquad j=1,2,3$$

We shall introduce the binary variables to indicate the validity of the inequalities above Let $y_j = y_{i_1,i_2,j} = 0$ if the corresponding inequality is satisfied, and $y_j = 1$ otherwise

Assume now that the left-hand sides of the inequalities are all bounded from above by some fixed positive number M. Such values in the given context can be easily provided for instance, the sum of the two longest edges of the storage volume (i.e , of the backpack main compartment) is an appropriate bound. Then

$$\max_j \; g_{i_1,i_2,j} \geq 0 \qquad \text{for all } i_1,\ i_2 \text{ where } \ i_1 < i_2$$

(I(I-1)/2 constraints)

can be equivalently expressed by the following mixed integer set of model constraints

$$\frac{L_{i_1,j} + L_{i_2,j}}{2} - (h^{+}_{i_1,i_2,j} - h^{-}_{i_1,i_2,j}) \leq M \cdot y_j \qquad j=1,2,3$$

$$y_1 + y_2 + y_3 \leq 2$$

It is emphasized that the strict fulfillment of these constraints, including the integrality conditions on the variables y_j and the proper decomposition of all terms $|c_{i_1,j} - c_{i_2,j}|$ is essential to assure non-overlapping object positions. The number of the new integer variables $y_j = y_{i_1,i_2,j}$ equals 3I(I-1)/2, this fact and the rigorous satisfaction of the additional 2I(I-1) constraints implies a potentially significant computational challenge

Accessibility / priority ranking

Let us consider again a pair of objects O_{k_1} and O_{k_2} , $k_1, k_2 \in \{1, \ ,I\}$, assuming this time that they belong to two different importance (accessibility) rank groups We shall require that whenever O_{k_1} is less important than O_{k_2} , the top level of O_{k_2} be at least on the level of the top of O_{k_1} so that O_{k_2} can be reached 'above' O_{k_1} Consequently, for all pairs such that $O_{k_1} \prec O_{k_2}$, as expressed by the given relation $R_{k_1} < R_{k_2}$, we shall require satisfaction of the inequality $v_{k_2,3} \geq v_{k_1,3}$. Denote by n(c) the number of items in rank class c, c=1, . ,c_{max} Then the number of the priority ranking based accessibility constraints is $\sum_c n(c) \cdot n(c+1)$. (The index of summation runs from 1 to c_{max} - 1)

Target centre of mass location

Given the centre of each packing object O_i, and assuming their symmetry and homogeneity, the resulting centre of mass of the total load in direction j, CM_j, is determined by the equilibrium relation:

$$CM_j = \frac{\sum_i c_{ij} \cdot m_i}{\sum_i m_i} \qquad j=1,2,3,$$

To include also the mass of the backpack, and possibly some preassigned load in it, the index i ranges from 0,1, . I.

The required closeness of $\mathbf{CM} = (CM_1, CM_2, CM_3)$ and its target location, denoted by $\mathbf{CM^0} = (C_1^0, C_2^0, C_3^0)$, can be expressed in several different ways For example, we can require the satisfaction of the following relation:

$$\| CM - CM^0 \| = \sqrt{(CM_1 - CM_1^0)^2 + (CM_2 - CM_2^0)^2 + (CM_3 - CM_3^0)^2} \leq d_{max}$$

This way, we have one additional nonlinear constraint in which $d_{max} > 0$ is a given model parameter

An alternative approach is to introduce the non-negative discrepancies e_j^+ and e_j^- between the positions of CM_j and CM_j^0, applying again the absolute value decomposition of the actual discrepancy.

$$CM_j = CM_j^0 + e_j^+ - e_j^-$$

(3 state equations)

Accordingly, suitable penalty terms $s_j \cdot (e_j^+ + e_j^-)$ can be added as components to the objective function (defined below) The non-negative weight factors s_j represent the importance of meeting the target location requirement by component CM_j.

Physical stability and tightness of packing

There are a number of non-equivalent ways to express packing stability and tightness requirements Basic physical principles would suggest to minimize the height of the resulting centre of mass **CM**, while also aiming at its horizontally symmetric location, relative to the central vertical axis of the pack. This approach may not be fully suitable in the present case, since instead we have explicitly assigned a target location for **CM** For this reason, alternative ways assuring stability and tightness are to be sought.

Considering the requirement of normal loading patterns, we can require that each object is packed as close as possible to some pre-assigned point $\mathbf{T}^0$ of the packing volume In many other related applications (e g., container loading) $\mathbf{T}^0$ could be the SW corner of the loading area, but in the present context, a symmetrically located point on the bottom of the pack is more appropriate This will assure that the packed items are not 'floating in space', and are as close as possible to each other (related to this point $\mathbf{T}^0$) It does not guarantee per se, however, that there will not be any empty 'gaps' among the (rigid) objects which can not be filled in, due to the size and particular configuration of the items. Again, one may like to parameterize the coordinate directions individually, consequently, we can derive (for instance) the following function form.

Let us consider the decomposition of the absolute discrepancy values between the centre of object c_i and $\mathbf{T}^0$, for each coordinate:

$$c_{ij} - T_j^0 = t_{ij}^+ - t_{ij}^- \qquad t_{ij}^+ \geq 0, \quad t_{ij}^- \geq 0$$

Then:

$$\text{minimize} \quad \sum_j r_j \cdot \left\{ \sum_i (t_{ij}^+ + t_{ij}^-) \right\}$$

where $r_j \geq 0$ are given multiplier parameters, yields an appropriate component of the aggregate objective function.

Objective function

Primary objective function term (expresses optimized tightness and normality of packing)

$$\text{minimize} \quad \sum_{j} r_j \cdot \left\{ \sum_{i} (t_{ij}^{+} + t_{ij}^{-}) \right\} \qquad r_j \geq 0 \quad \text{multiplier parameters}$$

Secondary objective function term (expresses optimized discrepancy from target centre of mass)

$$\text{minimize} \quad \sum_{j} s_j \cdot (e_{ij}^{+} + e_{ij}^{-}) \qquad s_j \geq 0 \quad \text{multiplier parameters}$$

Tertiary objective function term (additionally enforces correct absolute value decomposition in non-overlapping position constraints)

$$\text{minimize} \quad P \cdot \sum_{j} (h_{i_1,i_2,j}^{+} + h_{i_1,i_2,j}^{-}) \qquad P \geq 0 \quad \text{multiplier parameter}$$

3 4 3 Model Summary

A concise summary of the optimization model is included on the following page This version represents the mixed-integer linear program (MILP) formulation, which is somewhat simpler than the non-linear version, but at the expense of Euclidean measures of the discrepancies in desired and achieved centre of mass.

$$\text{Min} \sum_j r_j \cdot \sum_i \left(t_{ij}^+ + t_{ij}^-\right) + \sum_j s_j \left(e_j^+ + e_j^-\right) + P \cdot \sum_j \sum_{i_1=1}^{I} \sum_{i_2=i_1+1}^{I} \left(h_{i_1 i_2 j}^+ + h_{i_1 i_2 j}^-\right)$$

s.t.
$$L_{i1} = d_{i1} \cdot b_{i1} + d_{i2} \cdot b_{i1} + d_{i3} \cdot b_{i2} + d_{i4} \cdot b_{i2} + d_{i5} \cdot b_{i3} + d_{i6} \cdot b_{i3}$$
$$L_{i2} = d_{i1} \cdot b_{i2} + d_{i2} \cdot b_{i3} + d_{i3} \cdot b_{i1} + d_{i4} \cdot b_{i3} + d_{i5} \cdot b_{i1} + d_{i6} \cdot b_{i2} \quad \forall\, i=1,\ldots,I$$
$$L_{i3} = d_{i1} \cdot b_{i3} + d_{i2} \cdot b_{i2} + d_{i3} \cdot b_{i3} + d_{i4} \cdot b_{i1} + d_{i5} \cdot b_{i2} + d_{i6} \cdot b_{i1}$$

$$\sum_{k=1}^{6} d_{i,k} = 1 \qquad \forall i=1,\ldots,I; \qquad d_{i,k} \in \{0,1\}$$

$$c_{ij} = u_{ij} + \tfrac{1}{2} L_{ij} \qquad \forall i=1,\ldots,I;\ j=1,2,3$$

$$u_{ij} + L_{ij} \le B_j^{\circ} \qquad \forall i=1,\ldots,I;\ j=1,2,3$$

$$u_{i_1 3} + L_{i_1 3} \ge u_{i_2 3} + L_{i_2 3} \quad \forall\, i_1, i_2 \quad \text{such that} \quad R_{i_1} < R_{i_2}$$

$$c_{ij} - T_j^{\circ} = t_{ij}^+ - t_{ij}^- \quad \forall i=1,\ldots,I;\ j=1,2,3$$

$$CM_j = \frac{\sum_i c_{ij} \cdot m_i}{\sum_i m_i} \qquad \forall\, j=1,2,3$$

$$CM_j - CM_j^{\circ} = e_j^+ - e_j^- \qquad \forall\, j=1,2,3$$

$$c_{i_1 j} - c_{i_2 j} = h_{i_1 i_2 j}^+ - h_{i_1 i_2 j}^- \qquad \forall\, i_1=1,\ldots,I-1,\ i_2=i_1+1,\ldots,I,\ j=1,2,3$$

$$\frac{L_{i_1 j}}{2} + \frac{L_{i_2 j}}{2} \le h_{i_1 i_2 j}^+ - h_{i_1 i_2 j}^- + M \cdot y_{i_1 i_2 j} \quad \forall\, i_1=1,\ldots,I-1;\ i_2=i_1+1,\ldots,I;\ j=1,2,3$$

$$\sum_{j=1}^{3} y_{i_1 i_2 j} \le 2 \quad \forall\, i_1=1,\ldots,I-1;\ i_2=i_1+1,\ldots,I; \qquad y_{i_1 i_2 j} \in \{0,1\}$$

where
- u_{ij} is j^{th} coordinate of lower left corner of item i
- b_{ij} is given j^{th} border length of item i
- L_{ij} is actual length of item i in direction j
- c_{ij} is j^{th} coordinate of centre of item i in direction j
- m_i is mass of item i
- R_i is Accessibility Ranking of item i
- B_j° is j^{th} border length of pack
- CM_j° is j^{th} coordinate of target Centre of Mass
- T_j° is j^{th} coordinate of Target gravity attractor
- r, s, P are weighting parameters

3.5 Solution Approaches

The presented general formulation, in all model variants discussed above, leads to a mixed integer problem, with linear and nonlinear constraints, and linear objective function(s) One can immediately observe that the presence of both integer and nonlinear structural components poses a non-standard computational challenge. In the framework of the present study the number of objects in each packing kit varies (approximately) between 20 and 30 Even such relatively small problem sizes can be perceived to be non-trivial, as the computational experiments (discussed later) have also proved. The following solution strategies were considered, and then several of them actually tested

3 5 1 Mixed integer nonlinear programming (MINP)

As noted above, the presented exact MINP formulation does not allow the direct application of standard commercial solvers available to the APLCS Project. In fact, none of the most frequently used solvers (known to us) has a standard built-in MINP option. There exist a few specific add-on solvers; however, they are provided without a strict guarantee of finding the 'true', globally best solution. Notwithstanding the difficulties referred to, we wanted to exploit the possibility of finding approximate numerical solutions using the available tools (instead of replacing the model by some obviously inferior, heuristics based version). Alternatively, the development of a suitable new solver is certainly an option to consider. Below we shall briefly discuss some of the available program system types which can be applied, to approximate the solution of the APLCS model versions presented

3 5 2 Continuous nonlinear programming (CNP) / Mixed integer linear prog. (MILP)

From among the possible options, the well-known modelling and optimization systems MINOS (Murtagh and Saunders, 1987, Gill, Murray, Murtagh, Saunders, and Wright, 1988) and ZOOM (Marsten and Singhal, 1988) were applied in test runs Note that these, and several other solvers, are usually built-in options in algebraic modelling language environments Well-known examples of the latter are GAMS (Brooke, Kendrick and Meeraus, 1988), or AMPL (Fourer, Gay and Kernighan, 1993). Again, none of these systems contains a standard, 'all-purpose' MINP solver In the numerical examples presented below, we used GAMS (professional version), available to the APLCS Project. In GAMS, one of the built-in NLP solvers is MINOS; the MIP solver is ZOOM

The essential problem with the above-mentioned and most other widely used solvers lies in the fact that they are all based on local scope search algorithms In other words, given a sufficiently close initial approximation of a locally optimal solution, they can be reasonably expected to yield an improved approximation of that particular solution In case of continuous parameterization, standard analytical (linearity, or more generally, convexity) assumptions guarantee the global convergence of such procedures These conditions, however, are not satisfied in case of the presented APLCS model the binary constraints, and the nonlinear constraint set related to the non-overlapping location of packed objects do not satisfy the convexity requirements This way, the approximation of the globally best solution(s) can not be automatically guaranteed by any'conventional' local solution approaches

Observe also at this point that the presence of integer variables immediately leads into the realm of global (nonconvex) optimization Hence, for solving even the 'simplest' binary linear programs, exhaustive branch-and-bound (adaptive tree search), or other implicit enumerative strategies are needed In many such cases, for realistic problem-sizes the global solution is just approximated by the currently available techniques

In summary, it can be expected that the presented model or, in fact, any somewhat realistic formulation of 3D packing problems, inevitably requires computationally intensive solution procedures, which do not necessarily result in finding the globally best decision For this reason, a very brief discussion of rigorous and potentially applicable global optimization methods is also included

3 5 3 Global optimization (GO)

In contrast to the broad class of 'conventional' local search approaches, global optimization strategies explicitly seek for the 'best possible' solution, assuming that several local optima (of unknown location and quality) may also be present GO is a relatively new field of mathematical programming for a recent detailed account of the most typical models and solution approaches, consult for example Horst and Pardalos (1995).

Pintér (1995a) presents a general adaptive partition and search approach to solving GO problems, under very mild analytical (continuity or Lipschitz-continuity) assumptions Workstation and PC implementations of this approach to handle bound-constrained continuous or Lipschitzian GO problems are described, respectively, in Pintér (1995b, 1996) The program system LGO is based on the combination of global scope (Lipschitzian branch-and-bound, and stochastic search) and local scope (conjugate directions type) subalgorithms which can be used in both automatic and interactive modes. The PC implementation has a menu-driven user interface which effectively assists rapid application development.

Since the LGO approach is, in principle, directly applicable to the very general classes of continuous and Lipschitz problems, the MINP model formulated above certainly can be connected to (i e run within) LGO. This would, however, necessitate a significant programming and testing effort The program sizes resulting from the above APLCS model are likely to be quite large, in global optimization terms This probably would call for specialized, additional development of LGO However, this option can be considered as part of a continued study

The general importance of the cutting/loading/packing problem-class, of which the presented APLCS model is a special case, has been discussed above Hence, it would definitely be worthwile to investigate and compare exact, computationally viable model formulations, and strategies for finding their globally optimal solution. As an alternative approach, various heuristic sequential packing strategies can be investigated and compared in sufficient detail This work, however, has to be relegated to a subsequent, more extensive study

3.6 Summary of Illustrative Numerical Examples

For illustration and model validation, a substantial effort was spent on solving several test problems In these the number of items varied between 3 and 15. The trivially sized problems were used only to test the suitablity (or inapplicability) of the available standard solvers As emphasized earlier, the inherent difficulties are primarily due to the presence of numerous binary constraints, as well as the (essential) nonconvex non-overlapping location constraints Both MINOS and ZOOM (versions available to the project) are able to solve only extremely small problems (with 3-4 packing objects) to optimality Drawings made to illustrate these results show that they are reasonable, hence supporting the validity of the model. However, with growing problem size the numerical complexity increases fast, and apparently the solvers mentioned soon become non-applicable.

Let us illustrate the above issues by a few examples Using GAMS/MINOS to solve a packing problem with 12 items, the corresponding problem size is characterized by about 800 constraint rows, 700 (variable) columns, and 3000 non-zero variables. The MINOS/RMIP option reports optimality of a non-feasible solution, after a relatively short runtime However, manually forcing the satisfaction of the necessary integrality constraints eventually leads to a reported infeasibility.

Applying GAMS/ZOOM to the same problem of 12 packing items leads to about 1000 rows, 1600 columns, and 4000 non-zero variables The ZOOM runtimes experienced are usually noticeably higher than their MINOS counterpart, due to the much different search strategy applied However, these runs also end up reporting unsuccessful search, indicate infeasibility, or exhaust the available computational resources.

Another powerful commercial MILP solver, CPLEX, was then applied to the problem After much testing and judicious selection of solver parameters, a feasible solution for a dozen kit items was achieved While there is progress, several hours on an IBM Pentium was required to attain this solution, without attaining optimality However, it has succeeded in proving the viability of the modelling approach presented. As even this relatively small numerical example indicates, the solution of 3D packing problems is, typically, far from being trivial This fact, as well as the general and specific importance of such problems serves as a strong motivation to conduct further investigations

4.0 Summary and Recommendations for Future Work

In this report, the findings of a literature survey, model development work, and tentative numerical results are summarized. The available professional literature indicates that due to the inherent complexity of three-dimensional packing/loading problems, and the specific properties of the APLCS problem investigated, none of the earlier model types studied are directly applicable, hence, new model development is necessary Consequently, an exact model is formulated and presented The numerical experiments show the validity of the modelling approach Additional software development, and further, more extensive computational investigations are suggested, to bring the work presented here to full utilization.

Another important direction of extending the present APLCS study is to provide a toolkit to efficiently visualize the calculated packing (object arrangement) results. GAMS or AMPL per se do not provide such possibility; LGO already has certain graphics capabilities, but would need a relatively straightforward extension towards this specific application The use of engineering design software tools such as AutoCAD is certainly a possibility. There exist also other visualization options to explore. Numerous possibilities exist to apply the introduced model versions with context-dependent modifications also to other loading/packing/resource allocation problems

The optimization model is a powerful simulation tool to allow sensitivity analysis for pack design, kit selection and placement, and potential trade-offs between accessibility and other considerations such as load balance. The formulation is comprehensive, but the solution techniques for this class of problems require further development to produce robust solutions to practical problems. More research must be undertaken in this area. The AutoCAD interface provides a rapid evaluation tool for visualizing the results and further enhancing the prototype model

In future stages of the APLCS Project, this model will be connected to the related biomechanical model of load carriage being developed by the Ergonomics Research Group This will allow one to estimate the overall effect of loadings on the human body, and hence to determine good packing strategies for selected collections of items, and optimal pack shape for packs which have not yet been designed These simulations will provide a lot of valuable information prior to actually building prototypes and testing them in the lab

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14 ABSTRACT

(U) Parametric analysis of load carriage systems has allowed for increased understanding of relationships between system design characteristics and the impact of these design features on the bearer. Of significant research interest for the APLCS project are the issues of convenience, comfort, and capacity. Parametric design analysis in this phase of the project involved an evaluation of the effects of differing load placement on the centre of gravity and accessibility of kit, and the development of a computer model for optimizing load configuration, based on system centre of gravity.

Kit placement, for both civilian and military load carriage, has only been subject to general guidelines in the past. This study looked at the bulkiness and accessibility requirements of certain kit items, along with the versatility of current LCS at containing these items, with the aim of improving future LCS design and function. User group surveys and records of standard operating procedures provided models for kit placement, which were evaluated for location of centre of gravity and access to critical equipment. Soldier kit preferences and frequency of use were also established.

Optimization of load distribution for carriage is subject to multiple criteria, including physical constraints, desired load location and resultant forces, and accessibility requirements. Optimization software developed in this phase of the contract would allow for evaluation of varying LCS dimensions and kit combinations on target variables, such as contact forces. It is also possible to evaluate LCS design features, for improved loading capability.

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